Meaningful Learning Processes of Service Robots through Virtual Environments.

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Carrera de Ingeniería en Electrónica e Instrumentación.

Artículo académico, previo a la obtención del título de Ingeniero en Electrónica e Instrumentación.

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2 de febrero del 2024

Latacunga

Meaningful Learning Processes of Service Robots through Virtual Environments.

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Abstract. This paper presents a control scheme for navigation tasks of an aerial manipulator robot. The proposed controller prioritizes the kinematics of the system considering its high redundancy, which is composed of an aerial platform and an anthropomorphic 3DOF robotic arm, the proposed control scheme is decoupled, i.e., a task is defined for the aerial robot and another task for the robotic arm. To validate the proposed controller, different tests will be performed in a virtual environment and in a partially structured environment. To perform the simulation tests, a virtual environment is developed to visualize the behavior of the manipulator robot, in the simulation environment tasks are planned in the workspace and adjust the controllers, avoiding damage to the physical robot. Once the controllers have been adjusted and simulated, experimental tests are carried out with the aerial manipulator robot.

Keywords: UAV, Robotic arm, Aerial manipulator robot.

1 Introduction

The use of technology to carry out activities that favor the development and growth of humanity has been one of the main focuses of several research works. Therefore, the design and construction of robots capable of performing tasks considered as human beings, has evolved, developing robots that perform tasks in hazardous environments in order to prevent incidents or accidents to people, robots are intended to facilitate people's lives. [1]. That is why the applications of robots have taken great relevance in the life of modern man, and of course in scientific development. Currently, the services offered by different robots depend on their mechanical structure, presenting a wide variety of robotic systems. [2] [3] Within service robotics, there is one subdivision: *i) personal service robotics*, focused on generating a support in the daily activities of human beings such as: training, assistance to the disabled, security, surveillance, education and help with household chores, therefore, it has become an area of interest for the scientific community and *ii) professional service robotics*, are usually operated by a trained person who is designated to start, monitor and stop robot operation in applications such as welding, painting, loading, casting and packaging. [4] [3] This type of robot generates performance in industrial environments in structured or semi-structured environments.

Service robots can operate in different sectors and scenarios, depending on their technical specifications. This has led to the existence of variants of these robotic systems, one of which is the aerial manipulator robot [5] . It consists of an unmanned aerial vehicle (UAV) and a robotic arm. Aerial manipulators are used to perform different tasks, such as the manipulation and translation of objects [6]. Considering the precision of grip and movement, allowing activities in hazardous environments [7] [8]. In this context, aerial manipulator robots can carry out inspection and maintenance [9] [10] in extensive pipelines within the oil industry, security service in the military and other activities [11]. In this context, different control schemes have been developed, focused on allowing the robot to have an autonomous behavior. For what is considered to be the robot's kinematics [12]. Depending on the type of control required, I can provide navigation and manipulation tasks for the aerial manipulator robot in which, it can be studied in a coupled or uncoupled way UAV and robotic arm, i.e., two cases of control can be presented: *i) Uncoupled,* refers to when the UAV and the robotic arm are controlled separately and *ii) Coupled*, when the UAV and the arm are controlled as a single system. In addition, the controller design depends on the components that make up the robot, such as the degree of freedom of the robotic arm and the action it is intended to perform [13]. Works such as those mentioned above highlight the need to investigate advanced control strategies for this type of robots, whether in closed or open loop, depending on the task to be performed.

Thus, according to the above description, there is great interest in both the scientific community and the educational sector in developing new control techniques [14]. Therefore, having a physical structure of these types of robots and their commissioning is difficult due to the cost and maintenance of the robotic system. One of the alternatives for this problem is the simulation through platforms such as Unity 3D, Unreal, cryEnGINE, which allow the simulation and interaction with the robotic system in realistic work environments, i.e., that have the characteristics of the environment and the equipment to be worked on. In this way, a variety of virtual environments can be designed for simulation testing [15]. The inclusion of virtual environments focused on education is not only a visual aid, but also tests the operation of the robot in order to evaluate the performance of controllers, as well as the operation of the imported 3D robot. In this way, a virtual environment focused on meaningful learning allows students to make their contributions and express their concerns. In addition, they interact with a multimedia tool, which makes learning more enjoyable, becoming an interactive environment for knowledge construction [16].

This work focuses on the development of an interactive virtual environment, which will be used to evaluate the performance of the proposed control scheme. Consequently, this article presents an interactive and immersive virtual training system focused on meaningful learning [17]. In addition, it is proposed to implement a mathematical kinematic model of the UAV and the robotic arm, individually, which allows designing the advanced control scheme. The proposed control scheme is a decoupled control algorithm for the aerial manipulator robot (UAV and robotic arm). The proposed control algorithm will be implemented and then simulated in a virtual environment focused on meaningful learning and finally the results will be validated with experimental tests. For this educational process, it is important to consider what the individual already knows in such a way that he/she establishes a relationship with what he/she must learn [18]. In this context, meaningful learning is the acquisition of new knowledge with meaning, understanding, criticality and the possibility of using this knowledge in explanations, arguments and solutions to situations.

The following document consists of six sections including the introduction, section 2 details the conceptualization of the virtual environment process and the control simulation technique for the aerial manipulator robot; section 3 presents the kinematic model of the UAV and the robotic arm. Section 4 presents the proposed control scheme for the aerial manipulator robot. The analysis and results of the virtual environment and the control algorithm are shown in section 5 and finally section 6 presents the conclusions obtained in the research work.

2 Conceptualization of the Process

Virtual learning environments play an innovative role in the teaching-learning process. By interacting with virtual work environments, students put the theoretical part into practice, and immersion and interaction with the robot allows them to acquire new knowledge, generating a process of analysis and collaborative reflection. For the development of this work, several modeling techniques, external resources, 3D scanning, control algorithm design, including a process of experimentation, are used.

2.1 Methodology

Fig. 1 shows the methodology used, detailing the development stages that allow the validation of the proposed control scheme in a 3D simulator and experimental tests.

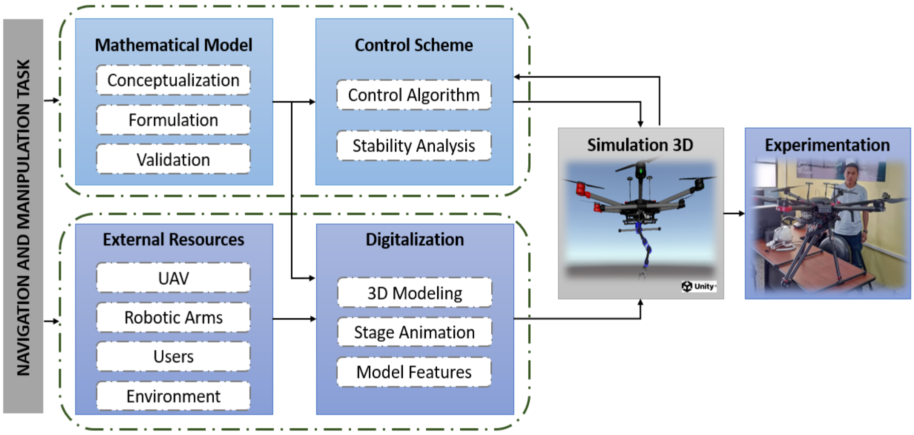

Fig. 1. Methodology for the control and virtualization of an aerial manipulator robot.

The proposed methodology for the navigation and manipulation task of the aerial manipulator robot consists of the following stages: *i) Mathematical model*, the mathematical model will be made, in order to obtain the kinematics of the robotic system. This is in order to represent the characteristics and restrictions of navigation and manipulation. To subsequently design and implement a control algorithm in Matlab software; *ii) Control scheme*, the proposed control scheme allows to evaluate the behavior of the aerial manipulator robot for navigation and manipulation tasks*; iii) External resources*, include 3D elements that are immersed in the virtual environment, such as: UAV and virtualized robotic arm, avatar and virtualized scenery; and finally *iv) Digitization*, the virtualization uses Unity3D software, prior to the use of CAD tools to model the elements, the files are exported in .fbx compatible with Unity software. In addition, elements are implemented that are as close to reality as possible. The virtual environment focused on meaningful learning allows testing the proposed advanced control algorithm in the virtual environment with the different elements described above.

Finally, the proposed control scheme will be tested for both the real aerial manipulator robot and the aerial manipulator robot virtualized in Unity. This will be done through the virtual environment, where several simulation parameters will be modified and the behavior of the control errors and their stability will be observed.

2.2 Virtual Environment

Virtual environments focused on the process of meaningful learning should consider an environment that resembles reality, allowing robot-user interaction, ensuring meaningful learning. Figure 2 details the implementation of a virtual simulator that allows interaction with a virtualized hexacopter for advanced control proposal.

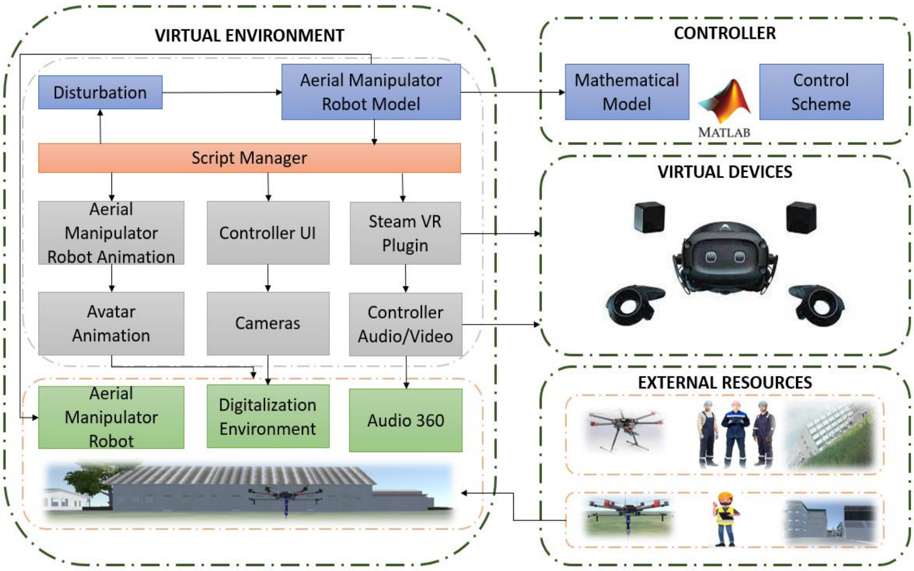

Fig. 2. Proposed scheme of the virtual environment.

Fig. 2, applies the full simulation technique, which consists in the use of Unity 3D. The same one that has all the features of the virtual environment. The mathematical model of the aerial manipulator robot and its perturbations are entered into the virtual environment. The virtual environment being interactive and immersive, the complete animation of the environment, i.e., audio and video, as well as the movement of the aerial manipulator robot for navigation and manipulation tasks in an unstructured environment is performed. The characteristics of the aerial manipulator robot are detailed in the mathematical model digitized in Matlab. Therefore, the proposed controller will also be inside Matlab for its corresponding simulation. The virtual environment is then configured to a Steam VR Plugin in order to display it on virtual reality devices. The virtual devices available for this project are the Vive Cosmos Elite. With this, significant learning will be achieved by having a wide control within the virtual environment and its simulation characteristics.

3 Robot Modeling

Aerial manipulator robots are characterized by a high degree of redundancy, combining the manipulation capability of a fixed-base manipulator with the navigation of an unmanned aerial vehicle with a fixed or rotary wing. According to the mobile robot to be analyzed, it achieves a displacement in the different axes of the Cartesian plane; in this case, a focus is made on UAVs and robotic arms.

3.1 Unmanned Aerial Vehicle

The Fig. 3 shows the unmanned aerial vehicle considered in this work.

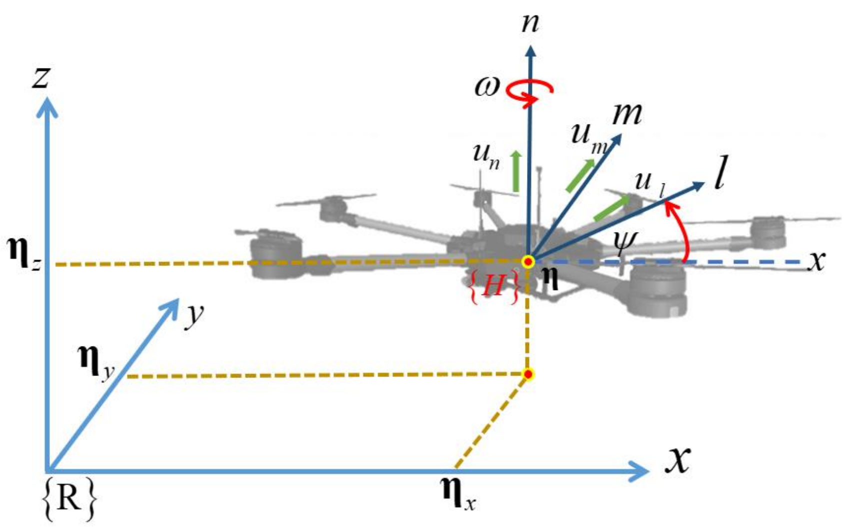

Fig. 3. Unmanned aerial vehicle, six rotating propellers.

The point of interest is considered at the center of the UAV to obtain the kinematic model of the UAV. The kinematic model of the UAV is composed of four velocities with respect to the moving reference system $H(l,m,n)$. The displacement of the UAV is defined by three linear velocities u_l, u_m, u_n and an angular velocity Ψ , which rotates about the vertical axis of the moving reference system $H(l,m,n)$. Cartesian motion of the UAV with respect to the inertial frame. {R} is defined as,

$$\dot{\mathbf{\eta}}(t) = \mathbf{J}_H \mathbf{u}(\mathrm{t}) \tag{1}$$

Where $\dot{\mathbf{\eta}}(t)$ represents the velocity vector of the hexacopter at the point of interest with respect to the inertial reference system. {R}, $\mathbf{J}_H$ is a non-singular matrix representing the motion of the UAV; y $\mathbf{u}(\mathrm{t})$ represents the UAV's maneuverability speeds.

3.2 Robotic Arm

The Fig. 4 shows the robotic arm considered in this work. The robotic arm is positioned at the UAV robot's center of mass with its operating end facing the ground. The robotic arm consists of 3DOF with its operating end as a point of interest.

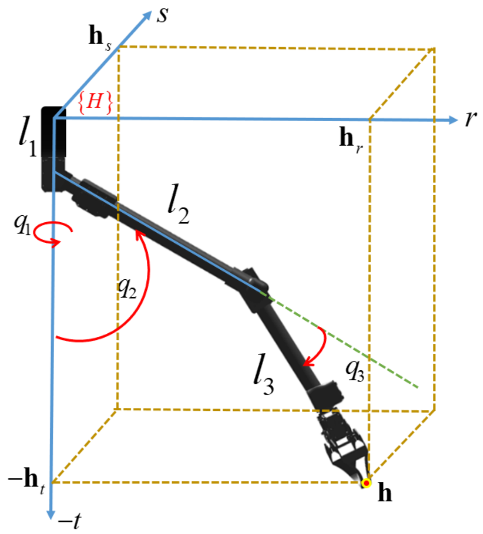

Fig. 4. 3DOF Robotic Arm

The kinematic model of a robotic arm is obtained from the derivative of the position of its end effector as a function of the derivatives of the velocities of the robotic arm. Therefore, the articular velocities of the robotic arm must be taken into consideration, such that q_1, q_2 y q_3 are positions of the robotic arm. Therefore, the equation describing the kinematics of the robotic arm is given by:

$$\dot{\mathbf{h}}(t) = \mathbf{J}_A \dot{\mathbf{q}}_A(t) \tag{2}$$

where $\dot{\mathbf{h}}(t)$ represents the velocity vector of the end-effector of the robotic arm, $\mathbf{J}_A$ is the Jacobian matrix of the robotic arm and $\dot{\mathbf{q}}_A(t)$ represents the articular velocities of the robotic arm.

3.3 Aerial Manipulator Robot

The kinematic model of the aerial manipulator robot is represented by the location of the end-effector, i.e., a function of the UAV and the configuration of the robotic arm. Fig. 5 shows the aerial manipulator robot represented in the reference system {R}. In this case, the rotation matrix of the aerial manipulator robot is taken into account: roll (ϕ), pitch (θ) and yaw (Ψ), which has pitch and roll angles at low speeds, which is why they take values close to zero, in order to have greater maneuverability of the aerial manipulator robot. Only the rotation around the Axis is considered n of the reference system {H}.

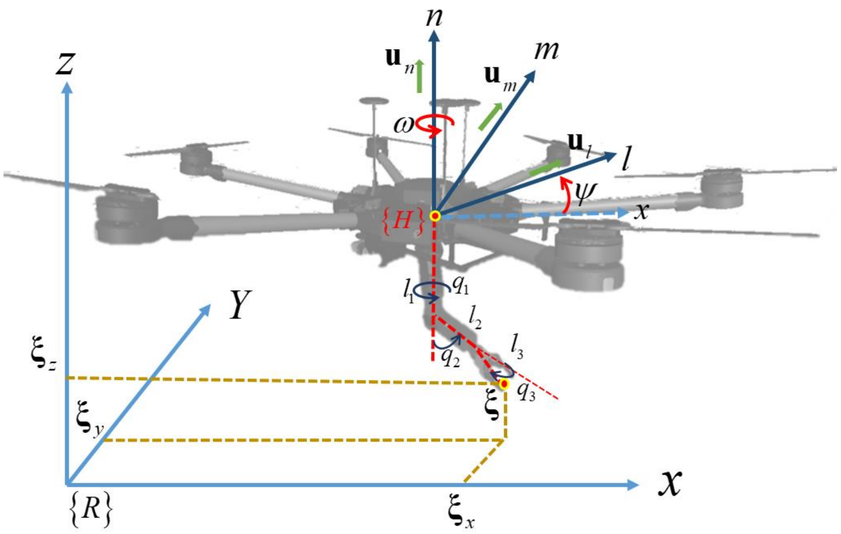

Fig. 5. Aerial Manipulator Robot

Consequently, the mathematical kinematic model for the aerial manipulator robot that determines the position of the end-effector of the aerial manipulator robot in a simplified form is defined as follows:

$$\boldsymbol{\xi}(t) = \mathbf{J}(\mathbf{q})\boldsymbol{\chi}(t) \tag{3}$$

where $\boldsymbol{\xi}(t)$ is the velocity vector of the end-effector of the aerial manipulator robot, $\mathbf{J}(\mathbf{q})$ is the Jacobian matrix of the robotic system that defines a linear mapping between the UAV velocities and the end-effector velocities and $\boldsymbol{\chi}(t)$ represents the control speeds.

4 Control Algorithm

In Fig. 6, a desired task will be proposed for the aerial manipulator robot, which is derived in subtasks, i.e., the robotic arm must perform a subtask and the UAV must perform another subtask, because each robotic system has a different controller. In this way, robotic systems will perform subtasks individually in order to perform a specific task in a decoupled manner.

The design of the kinematic controllers for both the robotic arm and the UAV is based on obtaining their kinematic model. The design of the position control of the robotic arm is based on the kinematic model taking into consideration that the robotic arm, being anchored to the UAV, moves and rotates together. A trajectory tracking control law for the UAV and a position control law for the robotic arm are proposed.

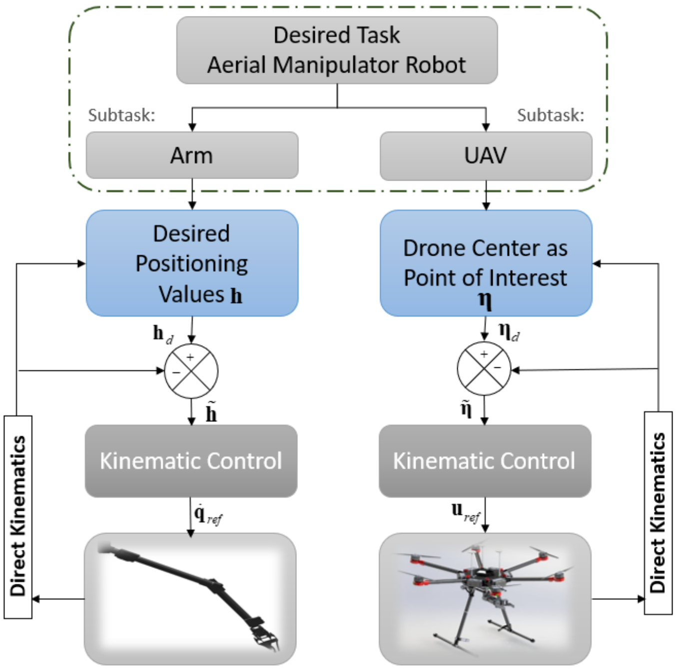

Fig. 6. Control Algorithm

4.1 Unmanned Aerial Vehicle

In this paper we propose a control law for trajectory tracking, described in the space XYZ. The control algorithm is based on the kinematic model of the UAV; therefore, the desired trajectory must be defined with respect to the reference frame. The proposed control law is:

$$\mathbf{u}_{ref} = \mathbf{J}_H^{-1}(\dot{\boldsymbol{\eta}}_d + \mathbf{K}_H \tanh(\tilde{\boldsymbol{\eta}})) \tag{4}$$

where, $\mathbf{J}_H^{-1}$ is the inverse Jacobian matrix of the UAV, $\dot{\boldsymbol{\eta}}_d$ the desired velocity vector with respect to the inertial reference frame {R}; $\mathbf{K}_H$ is the positive definite diagonal matrix that weights the control errors, and $\tilde{\boldsymbol{\eta}}(t) = \boldsymbol{\eta}_d - \boldsymbol{\eta}$ is the vector containing the trajectory tracking errors.

On the other hand, a candidate Lyapunov function is proposed to analyze the error behavior $\mathrm{V}_H(\tilde{\boldsymbol{\eta}}) = \frac{1}{2}\tilde{\boldsymbol{\eta}}^T\boldsymbol{\eta}$ of which deriving with respect to time $\dot{\mathrm{V}}_H(\tilde{\boldsymbol{\eta}}) = \tilde{\boldsymbol{\eta}}^T\dot{\tilde{\boldsymbol{\eta}}}$ and considering a perfect speed tracking, i.e., $\mathbf{u}_{ref}(t) \equiv \mathbf{u}(t)$ the closed-loop equation is obtained

$$\dot{\mathrm{V}}_H(\tilde{\boldsymbol{\eta}}) = \tilde{\boldsymbol{\eta}}^T\mathbf{K}_H \tanh(\tilde{\boldsymbol{\eta}}) < 0 \tag{5}$$

Therefore, if $\mathbf{K}_H$ is a positive definite matrix, we conclude that the control error converges to zero asymptotically, that is, it is asymptotically stable when time tends to infinity.

4.2 Robotic Arm

Using the same reasoning, the control algorithm for the robotic arm is based on the model obtained in subsection 3.2. The desired task of the robotic arm must be defined with respect to the UAV reference system {H}. The proposed control law is:

$$\dot{\mathbf{q}}_{ref} = \mathbf{J}_A^{-1}\left(\dot{\mathbf{h}}_d + \mathbf{K}_A \tanh\left(\tilde{\mathbf{h}}\right)\right) \tag{6}$$

where $\mathbf{J}_A^{-1}$ is the inverse Jacobian matrix of the robotic arm, $\dot{\mathbf{h}}_d$ the desired velocity vector with respect to the moving reference frame {H}; $\mathbf{K}_A$ is the positive definite diagonal matrix weighting the control errors; and $\tilde{\mathbf{h}}(t) = \mathbf{h}_d - \mathbf{h}$ is the vector containing the position errors.

In the same way as in the previous case, given the candidate Lyapunov function $\mathrm{V}_A\left(\tilde{\mathbf{h}}\right) = \frac{1}{2}\tilde{\mathbf{h}}^T\mathbf{h}$ you have $\dot{\mathrm{V}}_A\left(\tilde{\mathbf{h}}\right) = \tilde{\mathbf{h}}^T\dot{\tilde{\mathbf{h}}}$ and considering a perfect speed tracking, i.e., $\dot{\mathbf{q}}_{ref}(t) \equiv \dot{\mathbf{q}}_A(t)$ the closed-loop equation is obtained

$$\dot{\mathrm{V}}_A\left(\tilde{\mathbf{h}}\right) = \tilde{\mathbf{h}}^T\mathbf{K}_A \tanh\left(\tilde{\mathbf{h}}\right) < 0 \tag{5}$$

Therefore, if $\mathbf{K}_A$ is a positive definite matrix, we conclude that the control error converges to zero asymptotically, that is, it is asymptotically stable when time tends to infinity.

5 Analysis and Results

This Section presents the results obtained from the proposed control scheme, the simulation of the controller with the virtual reality environment in UNITY3D and the experimental results with the aerial manipulator robot composed of a 3DOF robotic arm and a UAV (Matrice 600pro).

a) Virtual Environment: In order to validate the simulator in Unity3D, a task for the UAV and a task for the robotic arm are defined. The simulator is used to adjust the gains of the controllers for subsequent experimentation with the robot. Figure 7 shows the movement of the aerial manipulator robot in the virtual environment.

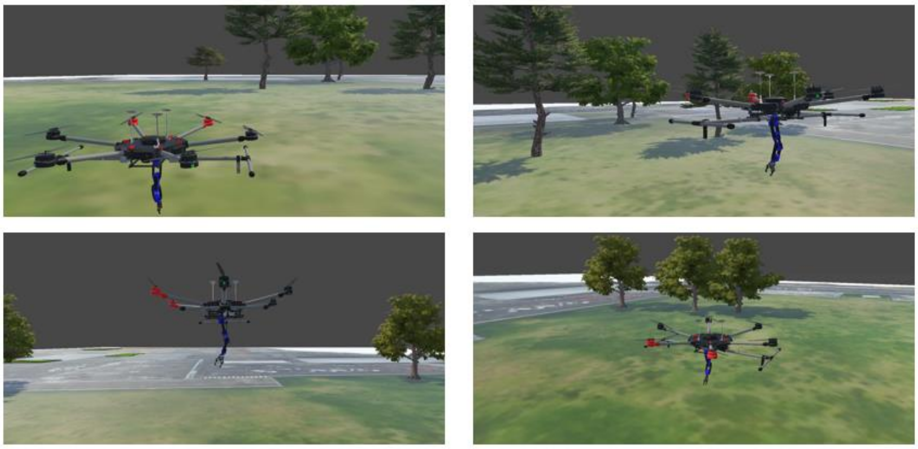

Fig. 7. Movement of the aerial manipulator robot in the Unity environment

b) Experimental Tests: Once the simulation of the controller in the virtual environment has been carried out and the controllers have been adjusted, the experimental test with the robot is carried out. The robot consists of a hexacopter (DJI Matrice 600 Pro), on which a 3DOF robotic arm was installed at the bottom of the UAV (see Figure 8). The prototype used can be seen in more detail at [19].

Fig. 8. Aerial manipulator robot used for experimental tests.

For the experimental validation of the controller, a desired task is proposed for the UAV and for the robotic arm. Table 1 shows the parameters of the desired task for the UAV robot and for the robotic arm, as well as the parameters of the UAV and robotic arm trajectory tracking controllers.

Table 1. Experimental parameters

UAV Controller parameters	Robotic Arm Controller parameters
x(0)=1.5, y(0)=0.5, z(0)=5 [m] $\Psi(0)=\frac{\pi}{6}$ [rad]	$q_1(0)=\frac{\pi}{9}$ [rad], $q_2(0)=-\frac{\pi}{6}$ [rad] $q_3(0)=\frac{\pi}{2}$ [rad]
$K_H = diag([0.5,0.5,0.5,0.6])$	$K_A = diag([0.3,0.3,0.3])$
$\eta_{d_x}(t)=4\cos(0.15t)-1$ $\eta_{d_y}(t)=4\sin(0.15t)-2$ $\eta_{d_z}(t)=8+0.6\sin(0.2t)+0.2\sin(0.5t)$ $\eta_{d_\Psi}(t)=\arctan\left(\frac{\dot{\eta}_{d_y}(t)}{\dot{\eta}_{d_x}(t)}\right)$	$h_{d_x}(t) = 0.2$ $h_{d_y}(t) = 0.2\cos(0.2t)$ $h_{d_z}(t) = 0.15\sin(0.2t)$

Figure 9 shows images of the real robot executing the task. The experimental testing environment for the decoupled controller is a partially structured environment. The testing environment is a region located at an altitude of 2860 m above sea level, so the airborne robot manipulator is affected by the average wind speed of 21 km/h. The sampling period used for the control is of 100 [ms], i.e., the maximum time for writing and reading data from the robot is 0.1 seconds.

Fig. 9. Movement of the aerial manipulator robot in the working environment.

Figure 10 shows the stroboscopic movement performed in Matlab with the real data obtained from the UAV. Figure 11 shows the UAV trajectory tracking control errors. It can be observed how the error $\tilde{\boldsymbol{\eta}}(t) = \boldsymbol{\eta}_d(t) - \boldsymbol{\eta}(t)$ as the experimentation time progresses, they tend to approach zero, i.e., the UAV follows the desired trajectory and orientation with small oscillations caused by wind disturbance. In $t \approx 45$ $[s]$ the UAV is positioned for the robotic arm to perform the defined task. This is the reason for the oscillation in control errors and in $t \approx 90$ $[s]$ the UAV continues with the task of trajectory tracking.

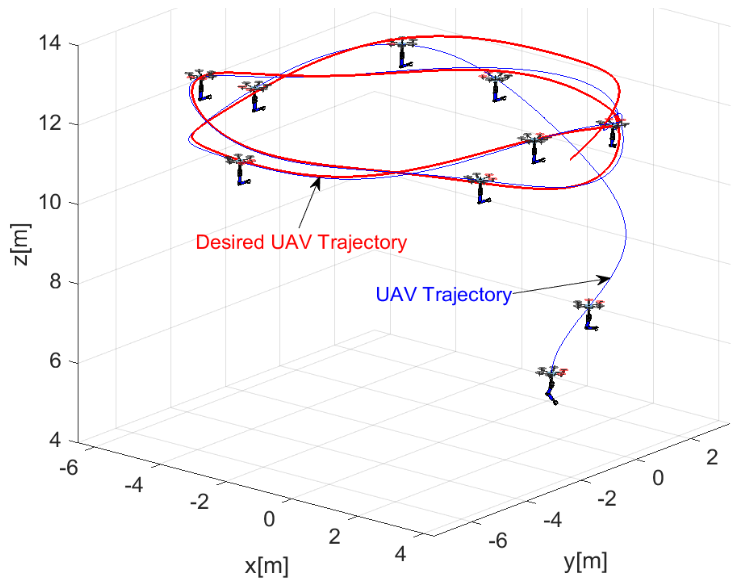

Fig. 10. UAV stroboscopic movement.

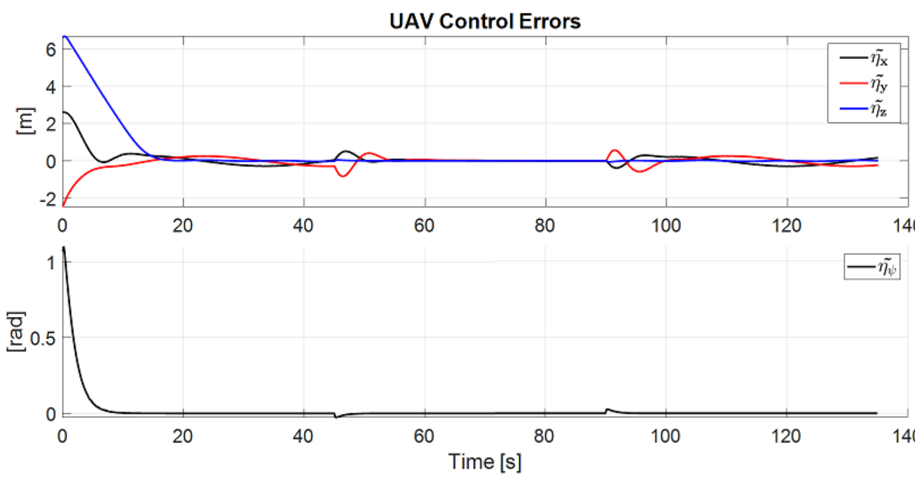

Fig. 11. UAV trajectory tracking errors during the experiment.

Finally, Figure 12 shows the stroboscopic movement executed by the robotic arm. And Figure 13 shows the error $\tilde{\mathbf{h}}(t) = \mathbf{h}_d(t) - \mathbf{h}(t)$ robotic arm trajectory tracking system. It can be seen how the error tends to zero asymptotically as the simulation time increases. In the first part of the experiment in $t < 45\ [s]$ the arm remains in a desired position and subsequently performs the defined trajectory tracking up to $t \approx 90\ [s]$.

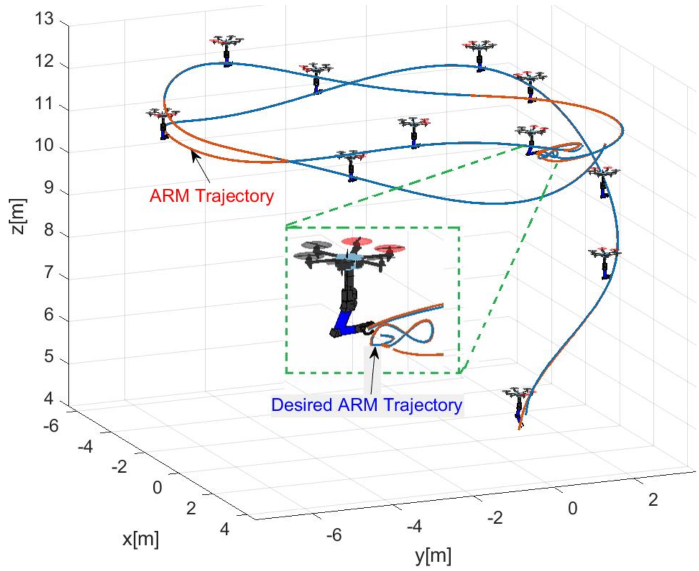

Fig. 12. Strobe movement performed by the robotic arm during the experiment.

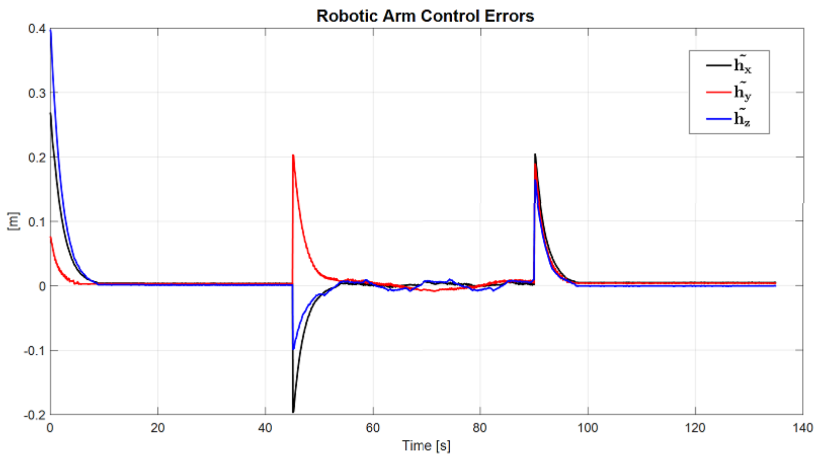

Fig. 13. Trajectory tracking errors of the robotic arm during the experiment.

6 Conclusions

The implementation of a virtual environment for meaningful learning processes for the control of an aerial manipulator robot has demonstrated its efficiency and feasibility to simulate and validate control algorithms in a scenario similar to reality. This allows future research on this application to develop a variety of advanced controllers, in order to give a greater applicability to these controllers, observing their behavior through the evolution of control errors in various scenarios, whether urban and/or rural. The proposed decoupled control scheme based on the robot kinematics has made it possible to propose independent navigation and manipulation tasks for the UAV and the robotic arm respectively. Experimental tests show how the controller maintains the control errors at zero, showing better stability when there are external disturbances produced by air currents during the execution of the tasks. Robotic arm control enables object manipulation tasks, while trajectory control enables navigation tasks. As future work, we intend to control the aerial manipulator robot to perform tasks with higher pressure, i.e., with an end effector that allows gripping objects or performing a welding process in spaces that are difficult to access.

Acknowledgment

The authors would like to thank the Universidad de las Fuerzas Armadas ESPE for their contribution to innovation, especially in the research project "Advanced Control of Unmanned Aerial Vehicles", as well as the ARSI Research Group for their support in developing this work.

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